LXXXI. *The Significance of the Bakerian Lecture of* 1843.

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[An account of several new Instruments and Processes for determining the Constants of a Voltaic Circuit. By Sir Charles Wheatstone, Professor of Experimental Philosophy in King's College, London. (Phil. Trans. Roy. Soc. cxxxiii. pp. 303–327, 1843) (1).]

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Contents.

Introduction.

Amid the stress of the present world upheaval another centenary has passed almost unnoticed, namely, that of the award of the Copley Medal by the Royal Society in 1841 to Dr. G. S. Ohm (2) in recognition of his arduous labours directed toward the elucidation of the mechanism of the electric circuit. Though Ohm's experimental discovery of the well-known law (1826) (3) and his subsequent theoretical treatment (1827) (4) have been remembered (5), the vast field of modern electrical technology has left little place for that important historical document which first founded a practical technique worthy of the great and simple truth which Ohm had revealed ; Sir Charles Wheatstone's lecture of 1843, about which I now write, makes in its generous appreciation of Ohm a suitable means of remembrance of the Copley award to this patient Bavarian investigator (6), and through its completeness, directness and simplicity affords perhaps a worthier focus for a centenary paper. It is proposed to review some of its more important physical aspects in their historical relationship.

* Communicated by Professor F. H. Newman.

The Aim of the Researches.

Wheatstone wrote (§ 1)[7] :—

" I intend in the present communication to give an account of various instruments and processes which I have devised and employed during several years past for the purpose of investigating the laws of electric currents[8]. The practical object to which my attention has been principally directed, and for which these instruments were originally constructed, was to ascertain the most advantageous conditions for the production of electric effects through circuits of great extent, in order to determine the practicability of communicating signals by means of electric currents to more considerable distances than had hitherto been attempted "[9].

Acknowledgment to G. S. Ohm.

" In this endeavour, guided by the theory of Ohm and assisted by the instruments I am about to describe, I have completely succeeded. . . . The theory we now possess is amply sufficient to direct us rightly in this inquiry, but experiments have not yet been sufficiently multiplied to enable us to obtain, except in a few cases[10] the numerical values of the constants which enter into various voltaic circuits ; and without this knowledge we can arrive at no accurate conclusions."

Sir Charles Wheatsone (1802–1875) greatly admired the work of G. S. Ohm (1789–1854), and perceiving that there was an urgent need for accurate practical measurement of resistance (an aspect which Ohm's researches had left largely unexplored) he applied his extraordinary experimental skill to a method which would be independent of fluctuation of e.m.f. of batteries[11]. This improvement of methods of resistance measurement resulted largely from the work of those investigators dealing with the telegraph, of whom Wheatstone was one. He wrote further (§ 2) :—

" The instruments and processes I am about to describe being all founded on the principles established by Ohm in his theory of the voltaic circuit, and this beautiful and comprehensive theory being not yet generally understood and admitted, even by many persons engaged in original research[12], I could scarcely hope to make my descriptions and explanations understood without prefacing them with a short account of the principal results which have been deduced from it."

The Data.

(1) Of these results were the removal of the vague terms intensity and quantity[13] and the reduction of the findings of many investigators in all parts of Europe to a few simple and general formulæ.

(2) " The electromotive force E is the agent which in a closed circuit originates electric current and in an open circuit produces ' electroscopic

tension ' [14] ; the resistance R is numerically equal to the reciprocal of the ' conducting power ' which term it supersedes in clarity " [15]

(3) " When the activity of any portion of the circuit is increased or diminished, either by a change in the electromotive force or in the resistance of that portion, the activity of all the other parts of the circuit increases or decreases in a corresponding degree, so that the same quantity of electricity always passes in the same instant of time through every transverse section of the circuit."

(4) Wheatstone still found it useful to refer to the concept of reduced length—that length of copper wire of a given uniform diameter, the resistance of which was equivalent to the sum of the resistances in the circuit—Ohm being the originator of this concept. For a circuit of two parts of reduced lengths λ, λ^1 connected in parallel, their combined resistance may be represented as $\frac{\lambda\lambda^1}{\lambda+\lambda^1}$.

(5) Sources of electric action differ only in the magnitude of their electromotive forces and their effect is modified solely by the resistance of the circuit.

(6) The electromotive force of any voltaic element depends not upon its dimensions but solely upon the nature of the metals and liquids in contact.

(7) On the above basis, Wheatstone stated the general law

$$F=\frac{nE}{\frac{nRD}{S}+\frac{rl}{s}},$$

where F=" the force " of the current,

n =the number of elements in series, each of electromotive force E,

R =the specific resistance of the liquid in each element,

D =the thickness of the liquid stratum between the plates,

S =the cross-sectional area of each plate in contact with the liquid,

r =the specific resistance of the connecting wire, of length l and cross-sectional area s.

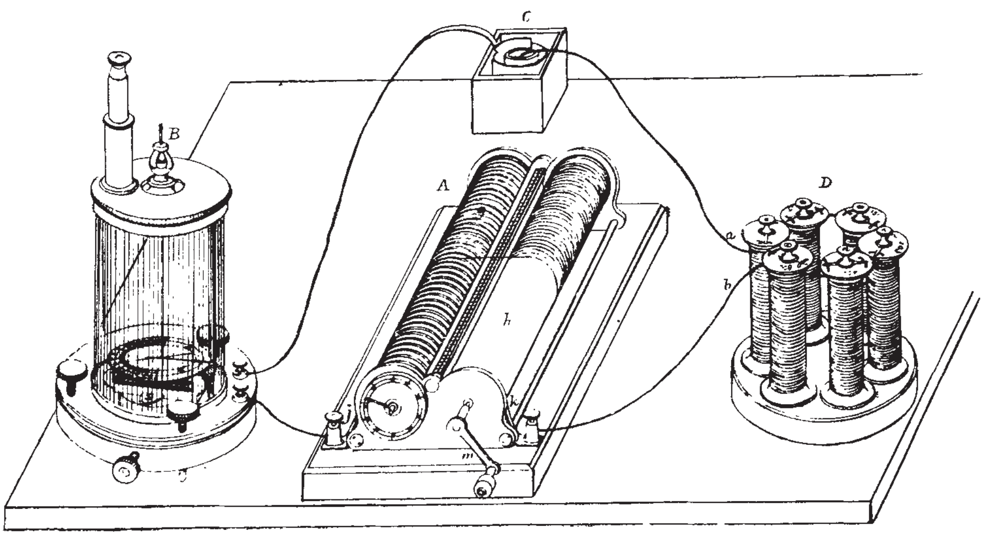
The above was the fullest and most precise statement made on the electric circuit previous to 1845 [16].

The Use of the Rheostat.

Wheatstone's rheostat marked a great step forward in experimental technique by enabling a current to be maintained constant when fluctuations in electromotive force occurred ; this latter factor had been mainly responsible for the tardy acceptance of Ohm's Law in scientific

circles [17]. Researches previously carried out with electric circuits depended for their accuracy upon the measurement of current through a galvanometer, *e. g.* "Fechner [18] measured the force of the current by the number of oscillations of the needle when placed at right angles to the coils, a very tedious operation; and others have employed the deviations of the needle, the corresponding degrees of force having been previously determined by some peculiar process, or inferred from some rule depending on the particular construction of the instrument. Another impediment to the use of a galvanometer to measure the force of a current arises from the changes in the magnetic intensity of the needle, which frequently occur, especially when it has been acted upon by too strong a current." (§ 4.)

Fig. 1.



The principle of the method used earlier by Fechner [19], by Lenz [20], and by Pouillet [21] was demonstrated by Wheatstone thus:—

For a simple circuit $F=\frac{E}{R}$.

Interpose a further resistance R^1, when "the force of the current" becomes

$$F^1=\frac{E}{R+R^1}.$$

Therefore,
$$\frac{F}{F^1}=\frac{R+R^1}{R}.$$

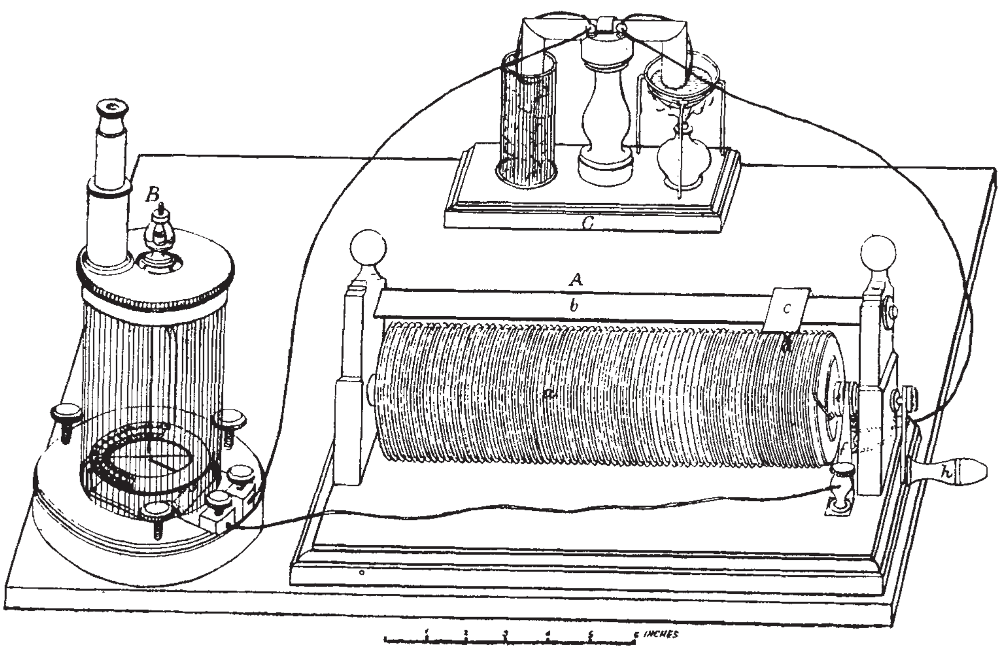
By using a rheostat capable of different low resistance values, Wheatstone removed the difficulty of knowing exactly the forces corresponding to different deviations of the needle. A similar instrument for low-

resistance circuits—the agometer—had been conceived by Jacobi in 1840 [22]. For high-resistance circuits Wheatstone used resistance coils [23] Two circuit arrangements by Wheatstone are shown in figs. 1 and 2.

A Practical Standard of Resistance.

Pursuing Ohm's original concept of reduced length, Wheatstone used a practical standard of 1 ft. of copper wire weighing 100 grains. Length and weight were chosen because small changes in diameter produce considerable changes of resistance [24]. The absolute system of Gauss was in existence [25], but its extension to include an absolute unit of resistance came with Wilhelm Weber [27]. Wheatstone's interests were

Fig. 2.



Two circuits used by Wheatstone, one "hydro-electric," the other thermo-electric.

A. Rheostats. D. Resistance coils.

essentially practical and there is no indication that he ever thought of anything of an absolute nature. In common with the majority of his contemporaries he failed even to give a name to the units in which he expressed electromotive force, current and resistance [27].

Determination of Resistance in a Circuit.

1. *Resistance Determined by the Method of Substitution.*

In a given electric circuit, replace the unknown resistance R by a suitably adjusted rheostat in order to produce the same deflexion θ in

the galvanometer Then R equals the resistance of that portion of the rheostat interposed.

2. *Resistance of a Galvanometer Coil.*

Place a cell of electromotive force E and internal resistance r, a galvanometer of resistance G, and a known resistance R in series.

The current $=\dfrac{E}{R+G+r}$.

The same current (represented by the same galvanometer deflexion) is now obtained by adding a further identical cell and increasing the resistance by the necessary amount λ by interposing the rheostat.

The current $=\dfrac{2E}{R+G+2r+\lambda}$.

These expressions lead to

$$G=\lambda-R.$$

3. *Internal Resistance of a Cell in terms of Reduced Length.*

Six methods, based upon Ohm's Law, are given ; Wheatstone's fifth method is outlined below :—

Two identical cells are in series with an external resistance. Using the notation already adopted.

The current $=\dfrac{2E}{R+2r}$.

Now put the cells "side by side" (*i. e.* in parallel) and introduce resistance λ by means of the rheostat in order to give the same galvanometer deflexion.

The current $=\dfrac{E}{R+r/2+\lambda}$.

Hence $r=R+2\lambda$.

In these researches Wheatstone admirably demonstrates the value of the null method. Classical researches in physics invariably show that a theory is commendable in virtue of its simplifying assumptions, and Wheatstone, with his "exactly equal rheomotors" (28), has this same idealism of approach. A recent writer has criticised this outlook (29).

Evaluation of Electromotive Force.

"The rheostat affords a most ready means of ascertaining the sum of the electromotive forces active in a voltaic circuit, without requiring for this purpose the aid of a rheometer (galvanometer) graduated to indicate proportional forces, or having recourse to the tedious process of counting the oscillations of a needle, employed by Fechner in his investigations." (§ 10.)

With a single cell of electromotive force E and a *total* resistance of R in the circuit, find the extra resistance λ to be introduced to reduce the galvanometer deflexion from 45° to 40°.

Next, with other cells of total electromotive force nE and the same external circuit, find the resistance λ' to be introduced by means of the rheostat (and resistance coils if required) in order to produce the same change in deflexion, 45° to 40°.

Then, in principle,

$$\frac{\mathrm{E}}{\mathrm{R}+\lambda}=\frac{n\mathrm{E}}{n\mathrm{R}+n\lambda}=\frac{n\mathrm{E}}{n\mathrm{R}+\lambda^{1}}.$$

Whence $\lambda'=n\lambda$. Knowing the ratio $n\lambda:\lambda$, the ratio $n\mathrm{E}:\mathrm{E}$ also follows.

Using this method Wheatstone demonstrated experimentally that

(1) the electromotive force of a cell is independent of its dimensions and is determined solely by the nature of the chemicals.

(2) n elements of electromotive force E are equivalent when in series to a total electromotive force of nE.

(3) the "contrary electromotive force" introduced into a circuit by a voltameter can be measured, using a rheostat: "The measure of this contrary electromotive force is obtained by subtracting the actual number of turns from the number of turns corresponding with the electromotive force of the circuit when the decomposing cell is removed from it." (§ 11.)

Wheatstone's work on electromotive force was extended by Lenz and Saweljew [(30)].

The Resistance of Liquids.

Wheatstone laid important foundations in this study. One of his methods involved the use of a column of the liquid in a glass tube "about two inches long and half an inch in internal diameter" and having one fixed and one movable platinum plate:—"I interpose in the circuit a small constant battery, consisting of about three elements, with the rheostat, the resistance coils, the galvanometer, and the measuring tube just described. The end of the piston being a quarter of an inch distant from the fixed plate, I fill the intervening space with the liquid, the resistance of which is to be measured. I then adjust the rheostat to bring the needle of the galvanometer to a determined point; this having been noted, I draw the piston back through the entire remaining space of one inch, and fill the vacancy with the same liquid; the needle will recede towards zero. I then diminish the resistance of the circuit by means of the rheostat and the resistance coils, until the needle stands at the same point that it did when only a quarter of an inch of the liquid column was interposed. The reduced length of the wire thus taken out of the circuit will be the measure of the resistance of one inch of the liquid. The contrary electromotive force arising from the decomposition of the liquid exists in the circuit during the whole process, and therefore does not affect the result." (§ 14.)

For a circuit represented mathematically by $\mathrm{F}=\mathrm{E}/\mathrm{R}$ before interposition of liquid, the resulting modified current F^{1} is given by $\dfrac{\mathrm{E}-e}{\mathrm{R}+x}$,

where e=the contrary electromotive force of the liquid and x its resistance.

The Wheatstone Bridge.

We now come to that part of Wheatstone's work which perpetuates his name in every textbook of electricity, namely, the invention of "the differential resistance measurer" (31).

Wheatstone noted that the rheostat was inapplicable when small differences of resistance were to be measured, and further, pointed out that Becquerel's differential galvanometer (32) was difficult to construct in practice such that currents of equal energy in the two coils would

Fig. 3.

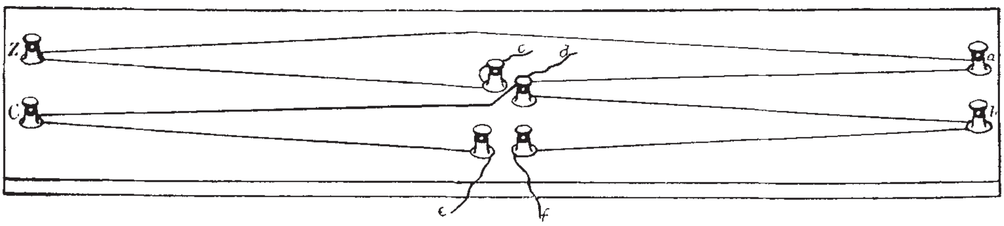
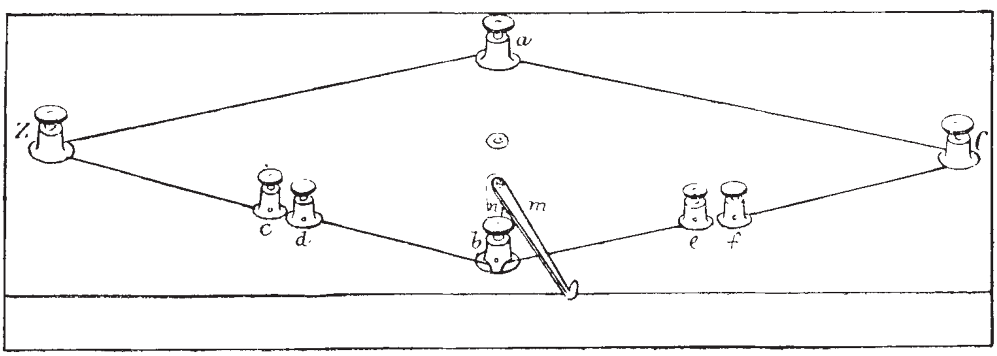


Fig. 4.



Two types of resistance bridge used by Wheatstone.

produce exactly zero deflexion in the needle. An attempt was therefore made to construct a differential instrument having all the advantages of Becquerel's galvanometer but none of its defects. Wheatstone's arrangement also proved to be applicable to any galvanometer.

In the first form of bridge (see fig. 3) four identical copper wires Zb, Za, Ca, Cb, are arranged upon a board such that a cell may be connected from Z to C, and the galvanometer from a to b. The equilibrium of the system is independent of the current (or any fluctuation in it) produced by the cell because equal currents always proceed through the galvanometer in opposite senses. This is due to the precisely equal circuits $ZbaCZ$ and $ZabCZ$.

For the purpose of interposing a known measuring resistance and a resistance whose value is required the wires *Zb*, *Cb* are broken from *c* to *d*, and from *e* to *f*. Thus the disturbance of equilibrium produced by introduction of the unknown resistance can be removed by the introduction of an equal measuring resistance (part of the rheostat known in terms of reduced length).

The second form (fig. 4), has a movable metal arm *m* able to rest on the wire at a desired point. This form was made more convenient by Kirchhoff [33], who introduced a uniform platinum wire, a movable contact, and a triangular lay-out ; the subsequent long, rectangular form was due to Siemens.

Observations relating to Galvanometers [34].

1. Wheatstone investigated the influence of the resistance of a galvanometer coil upon the circuit into which it is introduced and developed the theory of the shunt (§ 15).

2. By the theory of branched circuits established by Ohm, Wheatstone found the practical means of ascertaining what division of a galvanometer scale indicates half the current value corresponding to another given reading. In this way, a galvanometer scale may be calibrated, and desired fractions of the main current may be passed through the instrument (§ 18).

3. In § 19 a process of calibration, which superseded those of Nobili [35], Melloni [36], and Becquerel [37], was set down :—

(i) Determine the total resistance of the circuit when the needle reads 1°.

(ii) By means of the rheostat and resistance coils reduce the resistance to one half. Then the " force of the current " will be doubled.

(iii) Continue to reduce the resistance to one-third, one-quarter, etc., and the corresponding " force of the current " will be three, four, etc.

(iv) In general, if reduced lengths *a*, *b*, *c*, etc., must be removed from the circuit in order to advance the deflexion by 1° at each step, then the forces corresponding to each successive degree are

$$\frac{1}{\mathrm{R}},\ \frac{1}{\mathrm{R}-a},\ \frac{1}{\mathrm{R}-(a+b)},\ \frac{1}{\mathrm{R}-(a+b+c)},\ \text{etc.}$$

Concluding Remarks.

(1) The electrical researches of G. S. Ohm had not received unanimous support because succeeding investigators had not all been able to verify Ohm's Law with certainty. They had used cells (with consequent difficulties due to polarization) whereas Ohm had used thermoelectric elements. Nor were methods for current measurement and current regulation sufficiently reliable. The rheostat of Wheatstone and his

knowledge of galvanometry enabled accurate practical researches based on Ohm's Law to be made, and laid a basis for D.C. technology.

(2) Wheatstone made the first really clear statement in English of Ohm's Law and its associated definitions [38]. The effect of resistance and the factors determining electromotive force are explicitly stated, and the behaviour of a circuit containing liquid is expressed mathematically for the first time.

(3) The advances made by Wheatstone were essentially those of practical technique. His work suggested no generality respecting ranched circuits, nor any absolute standard of reference in resistance measurement. The value of null methods in galvanometry was stressed.

(4) Wheatstone's Bakerian Lecture was reproduced in Poggendorff's *Annalen* (vol. **lxii.**, pp. 499–543 (1844)), and his work had its influence upon contemporary physicists on the Continent, in particular on Professor M. Jacobi at St. Petersburgh, and his countrymen Lenz and Saweljew. The place of Wheatstone's work in the complete historical development of Ohm's Law has been treated elsewhere [39].

In conclusion, I thank Professor F. H. Newman, Vice-Principal of University College, Exeter, whose help and encouragement I much appreciate ; also Miss K. E. Perrin, Acting Librarian of the same College. who has kindly permitted to me very free use of the Library's facilities, and Mr. A. J. Ansley, to whom I am further indebted.

References.

(1) See also "The Scientific Papers of Sir Charles Wheatstone," Phys. Soc. Lond. pp. 97–132 (1879).
(2) Proc. Roy. Soc. iv. p. 336 (1841).
(3) G. S. Ohm, Schweigger's 'Journal,' Bd. 46, pp. 137–166 (1826).
(4) G. S. Ohm, 'Die galvanische Kette mathematisch bearbeitet.' T. H. Riemann : Berlin, 1827. Also in Ohm's 'Gesammelte Abhandlungen' (introduction by E. Lommel), pp. 61–187. Leipzig, 1889.
(5) Aus Georg Simon Ohm's 'Handschriftlichem Nachlass.' L. Hartmann : Munich, 1927. See also 'Nature,' Feb. 14th, 1889.
(6) G. S. Ohm was born on 16th March, 1789, at Erlangen, in Bavaria. His researches upon the electric circuit were performed under considerable difficulty during his spare time whilst a teacher at the Jesuit Gymnasium in Cologne, 1817–1826. Leave of absence during the year 1827 enabled the theoretical treatment (see (4) above) to be completed in Berlin.
(7) § refers to the sections of the Wheatstone lecture under discussion.
(8) The first verification and acknowledgment of Ohm's Law was by G. T. Fechner : 'Mass bestimmungen über die galvanische Kette.' F. A. Brockhaus : Leipzig, 1831. In 1837 independent work by the French investigator Pouillet, who first successfully used the tangent and sine galvanometers, also established the validity of Ohm's Law, and Ohm, in a letter written to Ludwig I. of Bavaria on 6th May, 1842, said that he did not expect Professor Pouillet "to adorn himself with foreign feathers." In fact, Pouillet was given considerable praise in some French treatises at the expense of Ohm, *e. g.*, M. J. Jamin wrote about "le remarquable travail d'un savant français, Pouillet, qui, à l'aide du galvanomètre, a retrouvé la loi de Ohm, encore inconnue en France

en 1837, et l'a fait définitivement adopter par les physiciens de tous les pays," *vide* Pouillet, 'Comptes Rendus,' iv. pp. 267–279 (1837)/ Letter to Ludwig I. "Akten des Bayerischen Staatsministerium, für Unterricht und Kultus München." M. J. Jamin: 'Cours de Physique de l'Ecole Polytechnique, iv. pt. 1, p. 30 (1888).

(9) As a result there arose the misconception about the velocity of electricity.

(10) Reliable experimental work involving Ohm's Law had been made by P. S. Munck af Rosenschöld in Lund (Pogg. *Ann.* Bd. 43, pp. 193–228, pp. 440–493 (1838)); Vorsselmann de Heer in Holland (Pogg. *Ann.* Bd. 46, pp. 513–537 (1839)); E. Lenz (Pogg. *Ann.* Bd. 34, pp. 418–437 (1835)); and M. Jacobi (Pogg. *Ann.* Bd. 48, pp. 26–58 (1839)) in Russia; and by Pouillet (Pogg. *Ann.* Bd. 42, pp. 281–297 (1837)) in France as mentioned. Researches by the last three investigators are most fruitful of experimental values. See also the letter to Ludwig I.

(11) Ohm actually determined his Law using thermoelectricity, and therefore with greater precision than batteries would at that time allow. Poggendorff suggested to Ohm the use of thermojunctions on the basis of Seebeck's discovery (1821). Antoine César Becquerel had devised a differential galvanometer in which any fluctuation of current produced equal and opposite magnetic fields at the needle. (*Annales de Chimie,* xxxii. p. 423 (1826).

(12) The main difficulty was polarization. Ohm's views were upheld by his countrymen Schweigger, Poggendorff, Pfaff, and Fechner, by Munck af Rosenschöld and Vorsselmann de Heer, and by Joseph Henry. Amongst his critics was the Hegelist G. F. Pohl in 'Jahrbücher für wissenschaftliche Kritik,' Nos. 11–14 (1828). Ohm has written: "Pohl is well-known to be arrogant and his blindness in despising my work is only due to his own attempt to restrain me. He is misguided his own animosity and is not led by truth." (Letter by G. S. Ohm to Prussian Ministry in Berlin, 6th March, 1828. No. 669 in 'Urkundensammlung des Deutschen Museums München.')

(13) See Ronalds, Phil. Mag. xlv. p. 261 (1815).

(14) The electroscopic tension mentioned by Ohm remained ill-defined until G. Kirchhoff (Pogg. *Ann.* Bd. 78 (1849)) identified it with electrostatic potential.

(15) The term "conducting power" had been used by the earlier investigators of electrical conductivity. (A. C. Becquerel, *Annales de Chimie,* xxxii. p. 423 (1826); H. Davy, Phil. Trans. cxi. p. 425 (1821)).

(16) A fair account existed in German: see P. O. C. Vorsselman de Heer (ref. 10 above).

(17) See letter from J. C. Poggendorff to G. S. Ohm, dated 26th April, 1844. No. 735 in 'Urkundensammlung des Deutschen Museums München.' The controversy relating to the origin of the electric current in the voltaic cell (contact hypothesis versus chemical hypothesis), together with the widespread faith in Hegel's philosophy in the German universities, were also contributory.

(18) See G. T. Fechner, 'Massbestimmungen über die galvanische Kette,' p. 5. Leipzig (1831). The principal types of galvanometer used previous to 1843 depended upon—

(i) Return of a deflected magnetic needle by a torsion-head (Ohm). (A bifilar suspension was not used.)

(ii) Oscillation of a magnetic needle having the rest position of its axis at right-angles to the magnetic field due to the current (Fechner).

(iii) Equilibrium of a magnetic needle hanging freely under gravity when submitted to action of the field due to current (Becquerel, improved by Lenz and Jacobi).

(iv) Measurement of the impulse due to momentary current (Lenz).
(v) Steady deflexion measured for a magnetic needle (uni- or bifilar suspension) as in a tangent galvanometer or similar instrument (Gauss, Nervander, Pouillet, Jacobi, Lenz.)
(vi) Alteration of the field direction in order to keep the needle at a definite position (sine galvanometer of Pouillet).
(19) 'Massbestimmungen über die galvanische Kette,' pp. 28–31.
(20) Lenz, Pogg. *Ann.* Bd. 48, p. 393 (1839).
(21) Paper referred to in (8) above.
(22) Footnote to § 4. Also see 'Athenæum,' No. 678 (1840). Wheatstone and Jacobi met in England in Aug. 1840 and exchanged ideas. Jacobi repeated Wheatstone's method on his return to Russia (Pogg. *Ann.* Bd. 54, 1841; Bd. 62 (1842)).
(23) The resistance box was first used by Werner Siemens (see 'Die Lehre vom Galvanismus.' G. Wiedemann. 2nd edition, Bk. 1, p. 239. Brauschweig (1872)).
(24) Previous to the conception of an absolute resistance standard each investigator used his own arbitrary standard, *e. g.* Lenz, "The resistance of 1 ft. no. 11 copper wire" (Pogg. *Ann.* Bd. 34, p. 418 (1833)). Vorsselman de Heer, "The resistance of 1 m. of Copper wire of 1 mm. diameter" (Pogg. *Ann.* Bd. 46, pp. 513–537 (1839)).
(25) K. F. Gauss, 'Intensitas vis magneticae terrestris ad mensuram absolutam revocata.' Göttingen, 1833.
(26) W. Weber, Pogg. *Ann.* Bd. 82, p. 337 (1851).
(27) "When the Committee was first appointed no coherent system of units for the measurement of electrical resistance, current, electromotive force, quantity, or capacity, had met with general approval. It was true that Professor W. Weber's absolute system existed on paper, but it was not understood or used by practical men." (Introduction to Reports of the Committee on Electrical Standards appointed by the British Association; Cambridge, 1913. This Committee first met in 1861 under W. Thomson (later Lord Kelvin).)
(28) The word "rheostat" is the only survival of a system of nomenclature (in which a cell was called a rheomotor) proposed by Wheatstone in this lecture.
(29) N. Campbell, Proc. Phys. Soc. xlviii. p. 708 (1936).
(30) Lenz and Saweljew, Pogg. *Ann.* Bd. 67, pp. 497–528 (1846).
(31) The principle had been proposed by Hunter Christie (Phil. Trans. 1833), to whom Wheatstone made acknowledgment.
(32) See ref. (11) above.
(33) G. Kirchhoff, 'Gesammelte Abhandlungen,' p. 15. Leipzig (1882). (From Pogg. *Ann.* Bd. 64 (1845).)
(34) Difficulties due to galvanometers had been stressed by G. S. Ohm (Schweigger's Journ. Bd. 63, pp. 1–26, 159–189 (1831), and the varied views of Jäger, Becquerel, Fechner, De la Rive, Nobili, Davy, Walker, Berzelius, Parrot, and Ritter were discussed.
(35) L. Nobili, 'Antologia di Firenze,' No. 142 (1832).
(36) Nobili and Melloni, Pogg. *Ann.* Bd. 27, pp. 439–455 (1833).
(37) A. C. Becquerel. See reference (11). (References 36, 37, 38 are not exhaustive.)
(38) 'Die galvanische Kette mathematisch bearbeitet' had appeared in English in 1841 in Richard Taylor's Scientific Memoirs, Vol. II. (Translation by Dr. W. Francis.) Ohm's exposition, like that of Fechner's, was often, however, tedious.
(39) H. J. J. Winter, M.Sc., Dissertation, University of London, 1940, from which this paper has been developed.